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DISPLAY SYSTEM IMAGE QUALITY

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SUMMARY

High performance aircraft employ several types of display systems including panel-mounted cathode-ray tube (CRT) displays, head-up displays (HUDs) and helmet-mounted displays (HMDs). These may be used to produce imagery from onboard sensors or to provide information in a symbolic format. There are a number of parameters that are used to characterize these displays such as resolution, contrast ratio, luminance, number of gray shades, line rate, interlace ratio, bandwidth, and modulation transfer function. In the case of the HUDs and HMDs, there are other parameters that further describe the display such as distortion, transmittance, field of view, exit pupil diameter, vergence, and field curvature. This paper will describe these systems, the measurement of various parameters, and how they affect the quality of the display system. In addition, methods will be presented that combine the display parameters with human visual system characteristics to produce image quality metrics that are related to operator performance.

CRTs

Panel-mounted displays can be either monochromatic or color cathode-ray tubes (CRTs) such as those used in television, solid-state liquid crystal displays (LCDs), or even thin-filmed electroluminescent. For this discussion, only CRTs will be described in detail, though most characteristics and measurements are the same or can be extrapolated to their solid state counterparts.

A monochromatic CRT is basically a glass vacuum tube that has an electron gun on one side and a curved or flat side that is coated with some type of phosphor, which is usually (but with exceptions) located on the opposite side. The electrons are accelerated toward the phosphor by the anode potential which is the voltage between the electron gun beam and the phosphor screen. There are numerous phosphor types (Westinghouse, 1972). Phosphor characteristics vary as to their chemical composition, phosphorescent color, spectral energy distribution (SED), and persistence. For example, P-43 is a yellow-green phosphor with a 543 nanometers (nm) peak wavelength and a medium class persistence, making it suitable for surveillance radar used in bright sunlight.

The different luminance levels of the picture are formed by modulating the electron-gun beam. The amount of emitted light is proportional to the number and energy of electrons striking the phosphor. The beam is magnetically focused to a very small spot on the phosphor screen. It is horizontally and vertically deflected by electro-magnetic coils or electro-static plates, which are synchronized to a camera or other source such as a computer. The pattern in which the beam is deflected is termed the raster. A standard raster is formed by first painting every other horizontal line to form one-half the picture (or field) and then the second half is filled in. The persistence of the phosphor and the raster refresh rate are chosen to minimize perceived flicker. Alternating fields having this structure are designated as having a 2:1 interlace, but other interlace ratios such as 1:1 or 4:1 are used for various applications. The two fields form a frame and the standard frame rate (in the US) is 30 hertz. The vertical resolution is fixed by the electron beam size and raster structure. Standard television (in the US) has 525 horizontal lines but approximately 15% are lost to beam retrace time, so only 450 lines are actually displayed. From 875 to over 2000 horizontal lines are used for the higher resolution applications. Horizontal resolution is limited by the beam spot size, phosphor type, and bandwidth of the electronics. The beam excites the phosphor and creates a spot with a near Gaussian luminance distribution. The spot size is typically around 8 mils at the 50% luminance point for larger CRTs and down to tenths of a mil for miniature CRTs.

A stroke-type CRT display differs from a standard display in that there is no fixed raster structure and, therefore, no complex pictures or imagery can be presented. Instead, lines and symbols are written directly on the phosphor under the control of an electronic symbol generator. Since there is no raster, stroke-written symbology appears continuous and the higher luminous outputs can be used for higher ambient, daytime applications. However, there is an upper limit as to the total number of symbols that can be simultaneously displayed. Some specialized CRTs can mix raster and stroke to provide an image with overlaid symbology.

Color CRTs are an extension of the monochromatic raster type display. Instead of one electron gun, there are three guns, one for each of the basic colors of red, green, and blue. Each color is modulated for its particular amount of information and is shot through a finely perforated metal plate termed aperture or shadow mask, which is

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located near and parallel to the phosphor screen. The shadow mask keeps the proper beam aligned with its corresponding phosphor. The screen has clusters of red, green, and blue phosphor dots, called triads. The triad is the basic resolution unit of a color screen. Each phosphor dot and triad may have a black surround. This black matrix acts to reduce the reflection of ambient light from the display face, giving the display better contrast. The structure of the triad is sometimes constructed of vertical stripes instead of dots. Monochromatic CRT phosphors have no discrete structure. Their vertical resolution is dictated by the horizontal raster structure. The horizontal resolution is much higher and is influenced by the electronic bandwidth and spot size. Color CRTs have the discrete, triad structure that strictly limits both vertical and horizontal resolution. Smaller triads produce higher resolution.

The F-16 C/D utilizes a (monochromatic) green, P-43 phosphor, panel-mounted multifunction display (MFD) CRT that can display both 525 and 875 line rasters. It has a very high luminous output of 3000 foot Lamberts (ft-L), which is attenuated to 1000 ft-L by a contrast enhancement filter. The F-16 A/B uses a panel-mounted P-43 type CRT to display radar and electro-optical imagery. Its resolution is similar to the MFD, but has a slightly lower peak output luminance of 2000 ft-L.

HUDs

Another type of display that uses a CRT is the modern HUD. This device has evolved from the optical gunsights of many years ago. This type of sight had an illuminated reticle or crosshairs reflected off a partially silvered mirror (or combiner), which was mounted directly in front of the pilot above the glare shield. Its superior aiming performance was due to the crosshairs being focused at optical infinity. This collimated image had parallel light rays the same as the light from the distant target, thus, parallax error was greatly reduced and aiming accuracy was increased. Parallax is the misalignment of two (or more) images because they appear at different optical distances. HUDs are essentially optical gunsights that use CRTs in place of the reticle to display information.

The basic components of a HUD (see Figure 1) are the image source, which is usually a CRT (but can also be a liquid crystal display), a mirror to fold the optical path, a collimating lens which focuses the light rays at optical infinity (parallel rays), and a combiner which is partially reflective and transmissive. The combiner reflects the CRT imagery while allowing the outside scene, which is also at optical infinity, to pass through, thereby superimposing both images for the observer. This is an idealized description that ignores the windscreen optical effects. HUD optics can be either nonpupil-forming or pupil-forming. A nonpupil-forming system is like a simple magnifying lens in that, as the observer moves his eye position, different parts of the image become visible. A pupil-forming system (an example being a telescope) has an area in which the entire image is seen as long as the eye is anywhere within the exit pupil area. The image disappears when the eye is outside of this area. The distinguishing factor is that in nonpupil-forming optics, the aperture stop is the simple magnifier. In pupil-forming optics, the exit pupil is the image of the aperture stop of the system as viewed from the image space of the system. Eye (and head) position is less critical for nonpupil-forming systems, but the observer must move around to see all the information. The total field of view (TFOV), expressed in degrees of visual angle, in a pupil-forming system is the same as its instantaneous field of view (IFOV). In nonpupil-forming systems, the IFOV is the same or smaller, but cannot exceed the TFOV. As shown in Figure 2, each eye has a slightly different IFOV which is termed the monocular IFOV. The area seen by both eyes is the binocular IFOV (BIFOV).

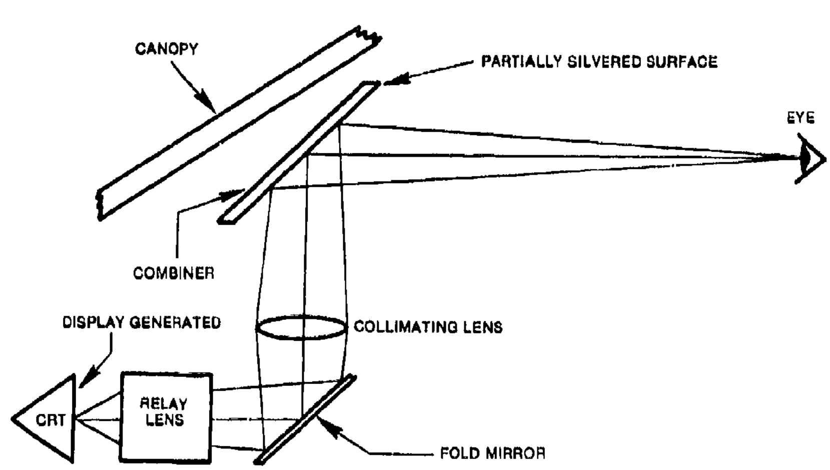


Figure 1. A refractive HUD.

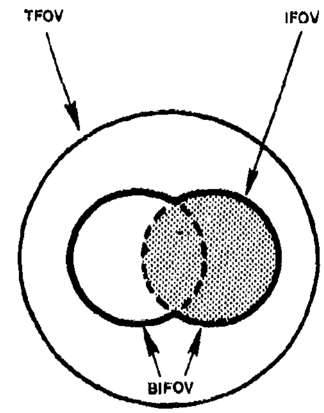


Figure 2. HUD fields of view.

Pupil and nonpupil-forming systems can be constructed using refractive, diffractive, reflective, and holographic optical elements. In the refractive system, the principal converging element is the collimating (refracting) lens. A typical refractive HUD system is shown in Figure 1. In these systems, the TFOV is always larger than the IFOV, though the vertical IFOV is usually very close to the vertical TFOV. The pilot must move his head around to observe all of the information. Binocular vision facilitates the acquisition of information in the horizontal plane. Referring to Equation 1, the BIFOV is greater than the IFOV by a factor of (1+2.5/d), where 2.5 is the average interpupillary spacing of the eyes (in inches) and d is the diameter of the collimator aperture. The larger the collimator aperture, the less pronounced the effect. The larger the collimator aperture, the larger the IFOV, but the weight of the lens increases quickly. A 25% increase in the IFOV may cause a 100% weight increase in refractive HUD optics.

$$\text{BIFOV} = \text{IFOV}\ (1 + 2.5/d) \qquad (1)$$

In order to increase the IFOV without incurring a severe weight penalty, reflective optics can be utilized. As shown in Figure 3, the principal optical element is a curved combiner which may also serve as the final collimating element. The IFOV is increased by increasing the size of the collimator or reducing the collimator to eye distance. If the system is designed to be pupil-forming, the IFOV and TFOV are the same. All information is visible as long as at least one eye is within the exit pupil. Figure 3 is a pupil-forming system. Reflective systems have been constructed up to 40 degrees which weigh up to 30 pounds. The larger combiners have optical aberrations that are usually corrected by relay lenses located between the CRT and the folding mirror. Combiners must have low, see-through, refractive errors and low reflective aberrations. The F-16 A/B and C/D models use nonpupil-forming, refractive HUDs.

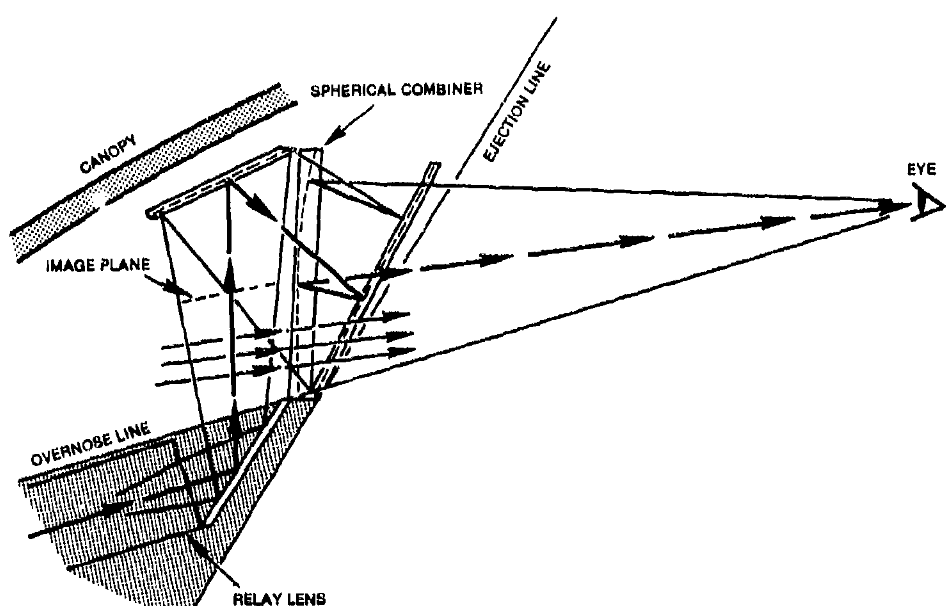


Figure 3. A reflective, pupil-forming HUD.

HUD performance may be further improved through the use of diffractive optics. Diffractive optics allow a more efficient use of the CRT light while maintaining good see-through transmissivity of the combiner. A diffractive element, which can be produced by several methods, has an interference or fringe pattern recorded within or on top of a substrate material. When light of the proper wavelength falls on this element at the proper angle, the interference pattern reproduces the original spherical wavefront. For HUDs, the diffractive combiner element is manufactured to reflect the precise frequency (about 12 nm wide) emitted by the CRT, yet pass all other light frequencies. The net result is a very efficient use of the available CRT light and very good transmissivity of the rest of the spectrum which is coming from the outside world. When viewing the outside world through the HUD combiner, it reflects (removes) green and passes the rest which results in a light rose or pink cast to the image.

The F-16 Low Altitude Navigation and Targeting Infrared for Night (LANTIRN) wide-angle HUD (see Figure 3) uses a holographically manufactured diffractive combiner. This HUD does not project a holographic image, it merely uses a combiner element that has a holographically produced diffraction grating that coincides with the 543 nm peak wavelength of the CRT's P-43 phosphor. This HUD is a pupil-forming system with a 28 degree field of view.

HMDs

Helmet-mounted displays are virtual image optical systems that are in many ways similar to HUDs, but with certain distinguishing features. HMDs often utilize miniaturized CRTs or light-emitting diodes as image sources. CRT size reduction has continued from around one inch diameter tubes to today's 0.25 inch, high resolution, high luminance tubes. Referring to Figure 4, the image is typically folded with a front-surface mirror, then collimated with a lens and reflected by the combiner into the observer's eye. If the design uses a relay lens, the HMD will be of the pupil-forming type. HMDs are most often pupil-forming systems. All of these electro-optical components are miniaturized and mounted in some fashion to the pilot's helmet. The combiner is either beneath the visor or an integral part of the visor. The displayed imagery can be a simple reticle, HUD-like symbolic flight information, or complex imagery from a sensor, such as from a forward-looking infrared system. If the display incorporates a reticle to aim a weapons system or helmet-mounted sight (HMS), it must include remote sensing devices that determine the helmet's line of sight. Remote sensing systems can use infrared or magnetic methods to determine helmet orientation. The HMS controls the sensor movement and the HMD displays what the sensor is aimed at, thereby forming a closed-loop system.

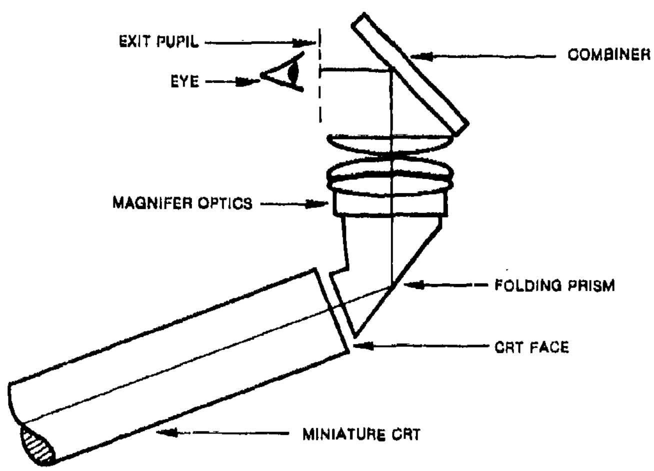


Figure 4. Idealized HMD system.

The basic design and function of CRT, HUD, and HMD systems have now been described in some detail. Each has a large number of parameters to be considered in its design. The realized performance of a particular display system is the result of the interaction of these numerous qualities, some of which have a more pronounced effect than others. The next section describes the major display system parameters and methods of their quantification. The last section will then show how some of these measurements can be combined with human visual system characteristics in an attempt to model and predict visual performance when using a display system of known qualities.

PHOTOMETRY

The measurement of several important display parameters involves the quantification of light energy. The basic tool for light measurement, when human vision is involved, is the photometer. This device measures light energy that is weighted by the photopic curve (see Figure 5), which represents the human eye's varying sensitivity to light as a function of wavelength, or color. Note that the eye is most sensitive to green and least sensitive to blue and red. The photometer measures luminance using foot-Lamberts (or NITS) as units. If a red and green light are adjusted to equal luminance, they would appear (near) equal in subjective brightness. If they were adjusted to have equal radiant intensity (watts/steradian), the green light would appear much brighter than the red light.

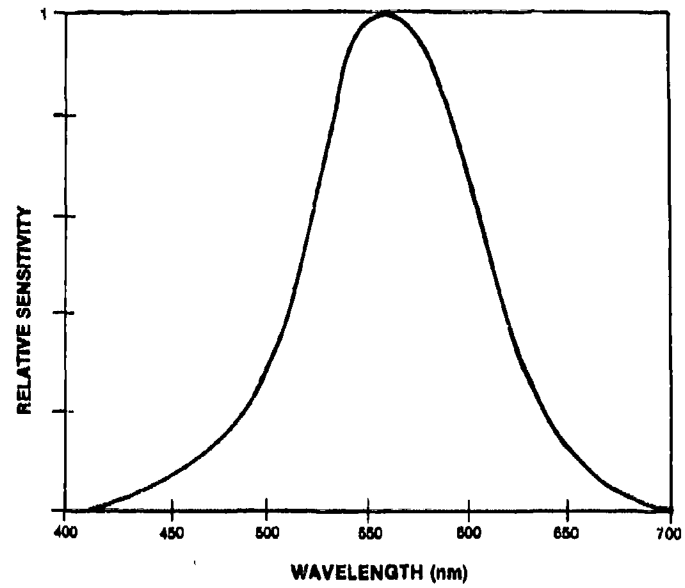


Figure 5. The photopic curve.

A diagram of a photometer is shown in Figure 6. Light enters the objective lens and is reflected by mirrors to the eyepiece to enable the observer to aim and focus the instrument. The first mirror has different sized holes (or apertures) that are seen as black circles (or slits) by the observer. The correctly sized aperture is selected for the object to be measured by rotating the mirror. The light to be measured passes through the aperture and covers the entire surface of the photomultiplier tube (PMT). Filters are used to weight the measurement so the PMT responds to light according to the photopic curve. The output voltage of the PMT is then converted and displayed. Since the photometer integrates all of the energy across the aperture area, the object to be measured must completely fill that area, or errors would occur. Luminance measurements of CRTs are unique in that the horizontal raster structure may affect the accuracy of the readings. A large circular aperture could be used to integrate energy from multiple lines, but it does not lend itself to scanning vertically oriented square-wave test patterns. A vertical slit aperture, oriented perpendicular to the raster structure, is best suited to measure CRTs. The photometer can be mounted on vertical and horizontal, motor-driven translational slides to aid the scanning of test patterns.

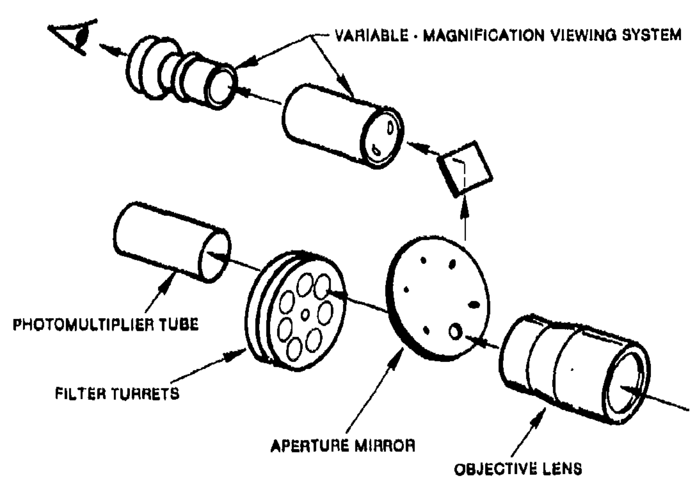


Figure 6. Variable-aperture photometer.

CRT PARAMETERS

CRT display characteristics can be categorized into geometric, electronic, and photometric entities. Table 1 lists these parameters (Task, 1979). For the purposes of this discussion, only the modulation transfer function (MTF) will be discussed in detail since it embodies many of the other parameters and is used extensively in the formulation of display image quality metrics.

Table 1. CRT display system parameters.

GEOMETRIC	ELECTRONIC	PHOTOMETRIC
Viewing Distance	Bandwidth	Luminance
Display Size	Dynamic Range	Gray Shades
Aspect Ratio	Signal/Noise	Contrast Ratio
Number of Scan Lines	Frame Rate	Halation
Interlace	Field Rate	Ambient Illumination
Scan Line Spacing		Color
Linearity		Resolution
		Spot Size
		MTF
		Luminance Uniformity
		Gamma

In the past several years, the MTF measure of display quality has received considerable attention. The MTF has been used as an indicator of the quality of film and photographic systems, of optical systems and lenses, and more recently of CRT displays. Theoretically, the MTF of a system indicates the percent modulation the system will pass as a function of spatial frequency for a sine-wave signal.

Since any signal (or picture) can theoretically be resolved into a set of component sine waves, it is possible to predict how the signal (picture) will appear after passing through a system with a known MTF. Therefore, if the MTF of a system is known, the signal (picture) degradation caused by that system can be calculated. However, the system must be linear and continuous before MTF techniques can be applied. Unfortunately, CRT displays are nonlinear devices, so care must be taken when applying MTF analysis to them. There are several ways to obtain the MTF of a CRT display. Most of these methods require mathematical manipulation of empirically measured signals and assume linearity of the CRT display. Mathematically, the MTF of a system is defined as the Fourier transform of the point spread function of the system. The point spread function is the resultant output signal from a system for a point or very narrow impulse input signal. Rigorous treatment requires the input to be of zero width and infinite height; practically, the spike needs to be much narrower than the spread caused by the system being tested. For CRT displays, the point spread function is typically obtained by measuring the spot profile produced on the face of the CRT by the scanning electron beam. This spread function is then used to obtain the MTF by applying the Fourier transform theory. Another approach is to assume the CRT spot profile is a Gaussian distribution (Equation 2) and calculate the MTF (Equation 3). A Gaussian distribution is used because the Fourier transform of a Gaussian distribution is easily obtained in analytic form, thus eliminating the necessity of using numerical Fourier transform techniques and a computer. CRT spot profiles are typically near Gaussian. Equation 3 is the normalized Fourier transform of Equation 2. Figure 7 shows a typical MTF generated by this method.

$$L(x) = Ke^{-1/2(x/\sigma)^2} \tag{2}$$

where:

L = luminance distribution
K = constant
x = spatial parameter (length)
σ = standard deviation of the Gaussian distribution

Taking the normalized Fourier transform of Equation 2 yields the MTF.

$$MTF(f) = e^{-2(\pi\sigma f)^2} \tag{3}$$

where:

f = spatial frequency
σ = standard deviation of the Gaussian distribution
$MTF(f)$ = fractional modulation

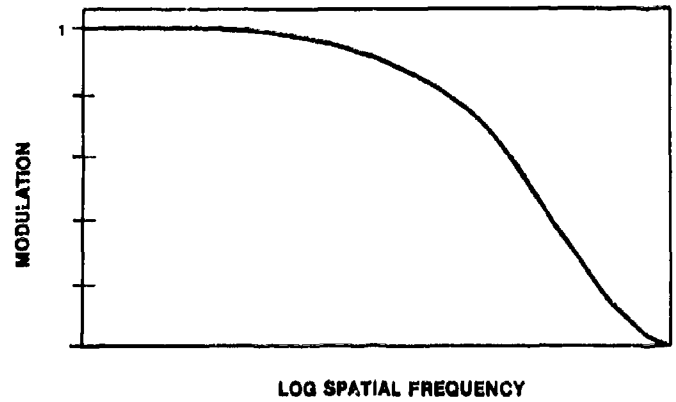


Figure 7. Typical MTF obtained from calculations based on assuming a Gaussian distribution spot profile as a point spread function.

Other methods of obtaining the MTF of a CRT display require Fourier analysis of square-wave, line, or edge patterns. In each case, the MTF must subsequently be calculated, assuming linearity of the display.

The direct method of obtaining the display MTF is to measure the modulation transfer of the display for sine-wave signals of various frequencies. The problem with applying this approach to CRT displays is that the input signal is electronic (measured in volts) and the output signal is photometric (measured in ft-L). Thus, the output to input ratio (percent of modulation transfer) is not clearly defined. Typically, this problem is circumvented by using a normalization procedure, the results of which can be misleading.

The sine-wave response (SWR) measurement technique (Task and Verona, 1976) was devised to avoid the problems inherent in calculating the MTF by using the various methods described. The SWR relates the maximum modulation contrast capability of the display to spatial frequency, measured directly, frequency by frequency. This differs from the MTF in two important respects: (1) it does not assume linearity of the CRT display, and (2) it is not a normalized function.

HUD PARAMETERS

The next section describes the optical quality measurement procedures that were adopted to evaluate the LANTIRN HUD (Task, 1983). The objective of these measurements was to determine how suitable the HUD optics were for matching human visual requirements. The measurements were directed to the optical components and did not include the cathode-ray tube (CRT) and symbology generation quality.

Measurements fell into two broad categories, those that characterized visual quality viewing through the combiner (effect on target acquisition) and those that concentrated on the visual characteristics associated with viewing the symbology. Table 2 shows the variables that were measured.

Table 2. Image quality measurement parameters.

COMBINER EFFECTS	SYMBOLOGY EFFECTS
MTF	Collimation
Optical Power	Image to Ghost Ratio
Spectral Transmissivity	Exit Pupil
Photometric Transmissivity	Reflections
Reflections	

Measurement procedures for each of these parameters will be described with its relationship to and effect on vision.

The MTF of an optical element (combiner) describes the transfer of contrast (or modulation) through the element. It is usually one of the most important quality measures for any imaging system since it can precisely predict the loss in image quality due to the imaging system and, therefore, accurately predict the loss in visual performance. There are several ways to measure the MTF of an imaging system. The most straightforward way is to input to the system high contrast targets that vary sinusoidally in luminance in one dimension. The contrast at the output end is then measured using a photometer and the ratio of contrast out to contrast in is calculated. This is the modulation transfer factor for that particular sine-wave spatial frequency target. This process is then repeated for other spatial frequencies resulting in a curve of modulation transfer factor versus spatial frequency, which is the MTF. Spatial frequency refers to the number of sine-wave cycles per unit length or per unit

angle, depending on the application. Since we are interested in the relationship to human vision, the units of cycles per degree are most appropriate for measuring the HUD combiner MTF. Modulation contrast is defined by Equation 4.

$$M_C = \frac{L_{MAX} - L_{MIN}}{L_{MAX} + L_{MIN}} \qquad (4)$$

where:

M_C = modulation contrast

L_{MAX} = peak luminance level

L_{MIN} = minimum luminance level

For measuring optical systems, it is not easy to produce high contrast, high quality sine-wave targets to directly measure the MTF. An alternate method that makes use of linear system analysis is equally effective and uses simple square-wave targets. This is the procedure that was used to evaluate the HUDs. A square-wave pattern can be mathematically represented by a series of sine waves as demonstrated by Fourier analysis. By inverting the series, it has been shown that a sine-wave response (MTF) can be calculated from the square-wave transfer function using Equation 5.

$$MTF(f) = \pi/4 \{ C(f) + C(3f)/3 - C(5f)/5 + C(7f)/7 \ldots \} \qquad (5)$$

where:

MTF = sine wave response
f = spatial frequency
$C(f)$ = square wave contrast transfer at frequency (f)

Normally, the MTF of a planar section of glass (such as a HUD combiner) should have an excellent MTF, i.e., no loss in contrast across the full spatial frequency sensitivity region of the human eye (0 to 60 cycles per degree). However, if there are reflections or light scattering effects, this will result in a lower MTF uniformly across all spatial frequencies. It is, therefore, very important to measure the MTF of the HUD under the conditions in which it will be used to include the degrading effects of reflections and light scatter. An alternative is to measure the HUD combiner in a dark room to eliminate these effects from the measurement and mathematically include them later as explicit reflection coefficients. This latter approach may be preferable, since it would then be possible to accurately predict the MTF (and, therefore, contrast and visual performance) for any ambient lighting condition.

A photometer with a narrow, vertical slit aperture was used to scan a square-wave target pattern with the HUD interposed and with the HUD removed. The MTF of each of these square-wave responses was then calculated. The MTF with the HUD in place (MTF of HUD and photometer) was then divided by the MTF without the HUD (MTF of photometer only) to obtain the MTF of the HUD by itself. This procedure was carried out in a dark room which resulted in an essentially flat MTF (no spatial frequency dependent losses) over the full range of spatial frequencies of the human visual system.

For the most accurate results, the aperture of the objective lens of the photometer should be no larger than the pupil diameter of the human eye under the luminance conditions of interest (2-3 mm diameter for daylight; 7-8 mm diameter for night). If a larger diameter is used, the MTF obtained does not correspond to what the observer will see, but will, in general, be somewhat poorer.

If the HUD combiner is indeed a flat plate, then it should have no optical power (no lens effects). However, if the combiner is a curved section, or is formed from glass sections cemented together, then it may contain some optical power. The effect of this optical power may combine with the HUD divergence/convergence errors and the windscreen lens effects to increase or decrease the possibility of diplopia (double imaging). The optical power was measured by mapping the angular deviation of light rays passing through the combiner from each eye position as a function of azimuth and elevation. The difference in angular deviation from the two eye positions was then calculated. The angular deviation was measured using an F-16 windscreen movement table and an optical angular deviation measurement device (Task, Genco, Smith, and Dabbs, 1983).

For most HUDs, the spectral transmissivity measurement is not really required, because the combiner coating is usually neutral with respect to wavelength. In other words, it passes a percentage of the light incident on it independent of wavelength. However, if the HUD combiner uses holographic optical elements (HOEs), such as the LANTIRN HUD, or if it has a dichroic or trichroic coating, the transmission of the combiner needs to be measured for each wavelength, resulting in a spectral transmissivity curve. A spectral scanning radiometer and a light box were used to make this measurement. The procedure was to make a spectral scan on the light box by itself,

then make a spectral scan of the light box through the combiner of the HUD. The second scan was then divided (wavelength by wavelength) by the first scan to yield the spectral transmissivity of the HUD. This process was done in a dark room to insure that reflections did not contaminate the readings. It is important to be careful of the size of the aperture of the radiometer to insure that all the light entering the radiometer has gone through the area of interest on the combiner. In the case of the LANTIRN HUD, the upper, "eyebrow" section was fairly narrow (see Figure 3), making it somewhat more difficult to measure its spectral transmissivity. Figures 8 and 9 show the spectral transmissivity through the eyebrow and central area, respectively, of a LANTIRN HUD.

Figure 8. Spectral transmissivity through the eyebrow portion of the LANTIRN HUD.

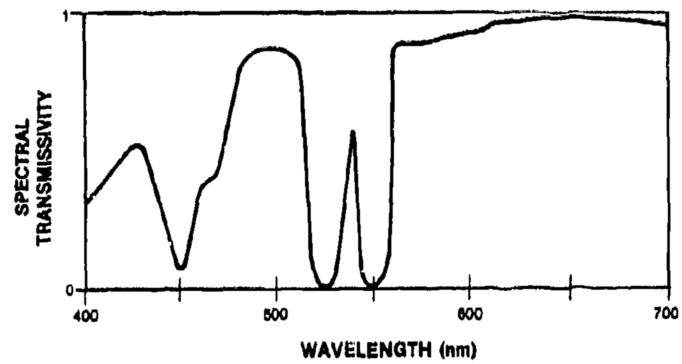
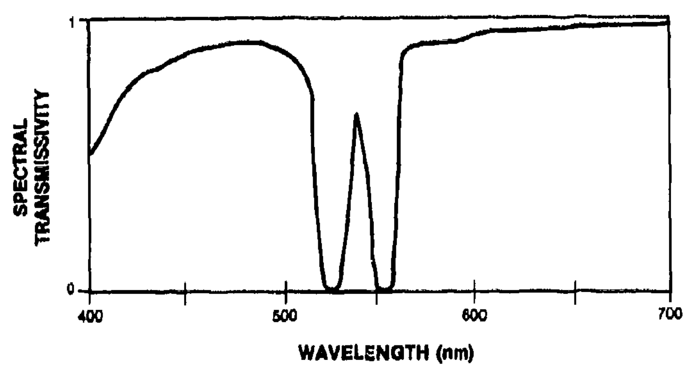


Figure 9. Spectral transmissivity through the central portion of the LANTIRN HUD.



The spectral transmissivity curve can be used to calculate the photometric transmissivity through the HUD of various objects of differing spectral distributions (colors). If the spectral transmissivity of the combiner is flat across all visible wavelengths, then the photometric transmissivity will be the same independent of the color of the object viewed. However, if the spectral transmissivity is not flat (as in the case of the LANTIRN HUD), then the photometric transmissivity is object dependent. As previously stated, the human visual system is not equally sensitive to all wavelengths of light. The eye's spectral sensitivity for daylight conditions is referred to as the photopic response curve (Figure 5), which is the basis for photometry. The photopic response curve peaks at about 555 nanometers and ranges from about 400 nm to 700 nm. The photopic transmissivity of the HUD depends on its spectral transmissivity, the photopic curve, and the spectral distribution of the object viewed. The photopic transmissivity in equation form is shown as Equation (6).

$$T = \frac{\int_{400}^{700} V(\lambda)\, S(\lambda)\, T(\lambda)\, d\lambda}{\int_{400}^{700} V(\lambda)\, S(\lambda)\, d\lambda} \qquad (6)$$

where:

T = photopic transmissivity
$V(\lambda)$ = photopic sensitivity curve
$S(\lambda)$ = spectral distribution of the object
$T(\lambda)$ = spectral transmissivity of the HUD

The spectral distributions of several objects were measured and the photometric transmissivity was calculated for each using data obtained on a LANTIRN HUD (production versions were expected to be better than the prototype), as shown in Table 3. These values were calculated assuming unpolarized light coming from each of the objects. In the case of blue sky, this is probably not a good assumption. Using the light box and a polarizer filter, the effect of polarizaton of light on the transmissivity was measured and is shown in Table 4.

Table 3. Photometric transmission through a LANTIRN HUD for various typically encountered objects.

OBJECT	EYEBROW	CENTER
Light Box (Measured)	54.8%	65.1%
Light Box (Calculated)	54.9%	65.1%
Blue Sky	46.0%	57.8%
Green Grass	46.8%	57.2%
Hazy Horizon	49.1%	59.9%
Distant Trees	47.5%	58.4%

Table 4. Effect of polarization on HUD transmissivity.

POLARIZATION	EYEBROW	CENTER
Vertical	61.0%	70.2%
Horizontal	55.9%	67.8%
None	58.4%	68.7%

The windscreen also has a polarization effect on transmissivity that combines and enhances the effect due to the HUD. The net result is an overall transmissivity that may vary by 10% to 15%, depending on the aircraft's orientation with respect to partially polarized skylight.

It is difficult to provide a specific measurement procedure for reflections because of the tremendous variations in the types of reflections that occur due to the different optical designs. In general, reflections are unwanted sources of light that are superimposed on the combiner causing a loss of contrast of both the outside world scene and the HUD symbology. In addition, the reflections may form real or virtual images of interior or exterior objects that act as a distraction to the observer. These reflections should be characterized as to the location of the image, the image source, and the relative luminance of the image with respect to the source (reflection coefficient). If the reflection has a different spectral distribution than the source, then it is necessary to measure the spectral reflection coefficient to properly describe the reflection. It is not possible to cover all these variations in the limited space available in this paper, so only one type will be considered to demonstrate the measurement approach to reflections.

In the case of the LANTIRN HUD, a reflection occurs from the flat HOE closest to the observer that reflects objects in the knee area of the pilot in the cockpit. This reflection is in a relatively narrow spectral band in the green wavelengths (543 nm). The reflection produces a virtual image of the knee area several inches forward of the combiner. A diffuse white light source (2700 Kelvin) was used as a "target" in the knee area. The luminance of the diffuse light source and its green reflection in the HUD combiner were both measured using a photometer. The reflection luminance was divided by the source luminance to obtain a reflection coefficient (to fully characterize this reflection, a spectral reflection coefficient should have been measured). This reflection coefficient varied somewhat across the face of the combiner, but was about 8-10%. This information, coupled with the MTF measurement, can be used to accurately predict the contrast loss viewing through the HUD for any given ambient lighting and target luminance condition. Equation 7 shows how this is done mathematically.

$$M_C = \frac{L_B T_W T_C - L_T T_W T_C}{L_B T_W T_C + L_T T_W T_C + 2RL} \qquad (7)$$

where:

M_C = Modulation contrast

L_B = Background luminance

L_T = Target luminance

L = Reflection source luminance

T_W = Windscreen transmittance

T_C = Combiner transmittance

R = Reflection coefficient of combiner

If R=0, there are no reflections and the contrast depends only on the target and background luminance. Note, however, that the resulting target contrast with reflections depends explicitly on the target and background luminances. This means that two targets with identical contrasts with their backgrounds will undergo different amounts of contrast loss for the same reflection situation if their luminances are different. Similar mathematical relationships exist for multiple reflections, chromatically selective reflections, etc. It should be noted that these contrast losses also occur for the HUD symbology, although a slightly different mathematical relationship applies.

Optical systems, such as HUDs, are typically composed of several optical elements, usually resulting in many air-glass interfaces. Uncoated glass will typically reflect about 4% of incident light at an air-glass interface. This effect results in unwanted real or virtual images of the object to be imaged (CRT symbology, in the case of the HUD). To minimize this effect, surfaces are normally coated with an antireflection coating. This substantially reduces the effect, but does not eliminate it, so there are usually ghost images that may be visible and distracting to the observer. There are several ghost images visible; two near the primary image and one to the right of the primary. A standard measurement (and specification) is the image to ghost ratio. This is determined by measuring the luminance of the primary image and then the luminance of the ghost images. The ratio of the primary image luminance to the ghost image luminance is the image to ghost ratio. In the case of the particular LANTIRN HUD ghost image, it was a very acceptable 300:1 ratio.

The original concept of a HUD was to place an aiming reticle and critical flight/weapon information in such a position that the pilot could keep his head out of the cockpit. The HUD symbology was collimated so that he did not have to refocus his eyes when switching from looking at the target and viewing the symbology, so the aiming reticle would appear at the same optical distance as the target. This eliminated parallax errors between the target and the reticle. Since outside targets are always far away, the HUD image was collimated or set for optical infinity. As with any physical parameter, there must be some tolerance allowed about the ideal value based on requirements; in this case, on the requirements of the human visual system and desired weapon system aiming accuracy. Since the HUD image and outside world target are viewed binocularly, there are two distinct concerns associated with the HUD image optical distance. First, can the eye lens focus on the imagery and the target at the same time? Second, will the two eyes fuse their separate views into one image or two? The first concern is usually no problem. However, the second concern, which also relates directly to parallax error (and therefore weapon system accuracy), is a major concern.

The best way to test for collimation is to measure the binocular convergence or divergence (vergence) of the HUD. This occasionally gets confusing because a HUD which has a diverging image causes the eyes to converge in order to fuse the image and a converging HUD image causes the eyes to diverge. It is necessary to have a measurement procedure for vergence for both the HUD image and of outside objects as they pass through the windscreen.

To measure the HUD image vergence, a laboratory developed binocular measurement device was used. This device (Task, 1981) was originally developed to measure the alignment of binocular display systems, such as two-eyed helmet-mounted displays, and was later generalized to HUDs and windscreens. Two objective lenses in front simulate the two eyes of an observer. Through a series of beamsplitters and prisms, the two images produced by these lenses are combined to form a single image viewed through an eyepiece. A color filter is placed in one side so that the two images can be identified. The two objective lenses are put in the design eye position of the HUD and the HUD symbology is viewed through the device. A moveable mirror is adjusted until the two images of the HUD symbology are fused into one. In this position, the device's "eyes" are converged (or diverged) to intersect at the plane of the HUD symbology. The device is then removed from the HUD and is moved toward or away from some convenient object until the two images are again superimposed (the mirror is not adjusted during this process). The angle of convergence is then calculated from the distance between the two lenses and the distance to the physical object. For converging HUDs, a slightly different procedure must be used. This general procedure has now been changed by introducing a reticle into the measurement device so that the convergence/divergence can now be read directly from the reticle. It should be noted that vergence tolerances depend on an individual's interpupillary distance (IPD). Those with eyes set wider apart will be more susceptible than those with a smaller IPD.

HMD PARAMETERS

There are many design parameters associated with HMDs. Careful consideration must be made in specifying these to insure the operational utility of the HMD for the particular application. Desired values of many of the parameters change, depending on the applicaton for which the HMD will be used. Table 5 provides a list of the design parameters (Task, Kocian, and Brindle, 1980), some of which will be discussed in this section.

Table 5. HMD design parameters.

Size/Weight/Center of Gravity	Image to Ghost Ratio
Monocular vs Binocular	Color/Color Contrast
Exit Pupil	MTF
Eye Relief	Image Source Quality
Apparent Field of View	Roll Stabilization Compatibility
Collimation	Combiner Reflectivity/Transmissivity
Distortion	System Transmission Efficiency
	Safety

By far the most common HMD has been monocular. The advantages of a monocular HMD are smaller size, less weight, easier alignment and lower cost. The binocular HMD does, however, provide an image to each eye. This prevents any possibilty of binocular rivalry occurring if the two images are identical or are a stereo pair. There has been concern with the potential for binocular rivalry in monocular HMDs for many years (Birt and Task, 1973; Hershberger and Guerin, 1975; Laycock, 1976). Many parameters (luminance, contrast, etc.) have been shown to have an effect on the subjective incidence of binocular rivalry (Hershberger and Guerin, 1975). In general, the more disparate the images to each eye, the greater the possibility for rivalry to be a problem. HMDs that present symbology only (no imagery) at a luminance level compatible with the external scene luminance show little or no potential to induce rivalry. In the application where the HMD displays imagery from a sensor, the potential for rivalry increases. The severity of this effect has not been determined. Individuals involved in HMD activities vary in their opinions from indicating that there is no rivalry problem to insisting that the problem is severe. However, most agree that the susceptibility to binocular rivalry depends heavily on the individual and the specific display conditions.

Most HMD applications require that the HMD image be collimated. This is important for target acquisiton. If the image is not collimated, then the image (e.g., a sight reticle) would move with respect to the target as the eye shifted laterally in the exit pupil. For other than direct target acquisition applications, it may be desirable not to have the image collimated. For example, if the HMD is used for viewing sensor imagery, it may be desirable to fix the image location in the same plane as the instrument panel, thus permitting the wearer to switch between the HMD image and the panel instruments without changing his eye accommodation distance. This may also decrease the potential for binocular rivalry for viewing outside the aircraft as the observer would look through the HMD scene when observing the exterior scene, although some studies have not shown this effect for subjective rivalry assessment.

Distortion occurs as a result of nonlinear transformations from the image source through the optical system. Typically, distortion appears as barrel or pincushion-like in rotationally symmetric optical systems (see Figure 10). However, HMDs using a parabolic visor as an optical element in the HMD optical chain suffer from a parabolic distortion (see Figure 11).

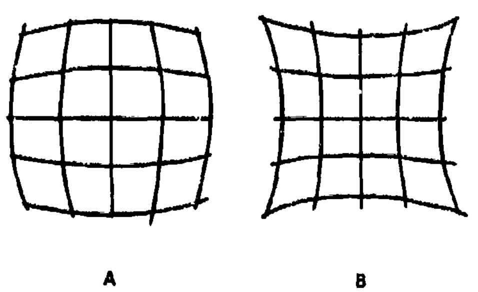


Figure 10. Typical distortion in rotationally symmetric optical systems: (A) barrel distortion, (B) pincushion distortion.

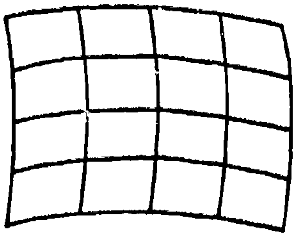


Figure 11. Parabolic distortion increases by the use of the parabolic visor.

Barrel and pincushion distortion may or may not be severe enough to require special correction, but parabolic distortion does. In general, the distortion and other aberrations are reduced as the number of optical elements is increased; however, this causes an undesirable increase in weight. A reasonable compromise between number of elements (weight) and optical aberrations must be achieved. Also, depending on the technology used, a particular optical design may employ either $F(\theta)$ or $Tan(\theta)$ mapping. For $F(\theta)$ mapping, the image field angle is proportional to the image source chordal

height, whereas, in Tan(θ) mapping, the tangent of the field angle is proportional to the chordal height of the image source. The characteristics of the image source must be matched to the type of optical mapping. Field curvature and astigmatism may also present problems, especially as the field of view for a particular design is increased. Field curvature can easily be corrected by attaching an appropriately shaped fiber optic faceplate to the image source. Distortion and mapping problems can be corrected by the addition of compensation electronics within the CRT deflection amplifier signal path. An often used approach to this problem is to first generate a mathematical representation or least squares fit of the distortion which must be compensated for and then determine the number of significant coefficients for a given percent decrease in distortion at the observer's eye. The selection of these coefficients must also be balanced against what represents a practical requirement for the electronics hardware. Critical for the hardware is the small signal bandwidth requirements that the compensation electronics must meet based upon either the highest line rate at which the system must operate in a raster mode or the step response/settling time characteristics for a stroke-written mode of operation. Due to the methods which most analog circuits use to generate terms with arbitrary exponents, the inclusion of a second order term will approximately double, and the addition of a third order term will nearly triple, the bandwidth requirements for the compensation circuits. Depending upon signal bandwidth requirements, the inclusion of only a few higher order compensation terms will, with current technology, severely strain state of the art performance for the analog multipliers that are generally used in such applications, as well as the signal-to-noise performance of supporting electronics. The above considerations are an illustration of the necessity for considering all components of the helmet-mounted display system early in the design development process so that appropriate trade-offs can be made.

IMAGE QUALITY METRICS

Any calculated measure of image quality must include characteristics of both the human visual system and the display imaging system. There are many measures of each of these but the ones most often employed in developing image quality metrics or figures of merit are the MTF for the display system and the contrast threshold function (CTF) for the visual system. The following sections describe the MTF and the CTF and ways that they have been combined to form image quality metrics.

As previously described, the MTF is formally defined as the real part (or modulus) of the normalized Fourier transform of the point spread function of the system (Gaskill, 1978). In addition, it is only applicable to linear, continuous, and homogeneous systems. In practice, these restrictions are ignored and the concept of MTF is applied in a much simpler fashion. The MTF of a complete display system (input sensor, video electronics and display monitor) can be measured directly by imaging high contrast sine-wave test patterns through the system. The ratio of the output contrast to the input contrast is the modulation transfer factor for the spatial frequency of the test pattern. The collection of modulation transfer factors as a function of spatial frequency is the MTF. Another way of thinking of the MTF is that it describes the maximum amount of contrast possible as a function of spatial frequency (Task and Verona, 1976). An example of a typical display system MTF is depicted by the upper curve in Figure 12. Note also that the spatial frequency may be presented in several types of units. For example, cycles per inch, cycles per millimeter or cycles per display width describe the spatial frequency in linear units. More appropriate for human observer related situations is to describe the spatial frequency in angular terms such as cycles per degree (cpd) or cycles per milliradian.

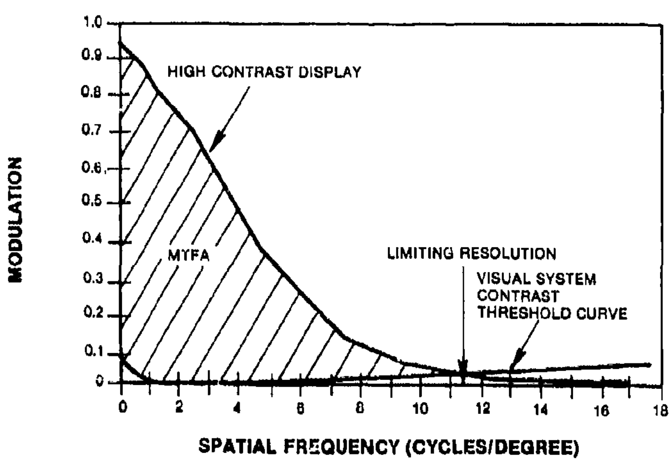


Figure 12. Pictorial representation of MTF, MTFA, and limiting resolution.

Human visual capability can be measured with a related technique using sine-wave test patterns. The procedure is to have the observer view a sine-wave test pattern that has a contrast so low that he/she cannot detect it. The contrast is then increased until the individual can detect the pattern. The contrast at which detection occurs is then recorded and the procedure is repeated at other spatial frequencies.

The resulting graph of detection contrast versus spatial frequency (Cornsweet, 1970) is called the contrast threshold function (CTF). The reciprocal of the contrast threshold function is often used to describe visual capability; this is called the contrast sensitivity function (CSF). It should be noted that the CSF is not the same as the MTF of the human visual system (Snyder, 1985). There are many variations in procedures for measuring the human visual contrast threshold function which give different results, but the basic goal is the same: determine the visual threshold contrast of a sine-wave test pattern.

The display system MTF and the human visual system CTF can be combined to form a class of image quality metrics (Borough, et al, 1967; Snyder 1974; Task, 1979). Figure 12 shows both the display system MTF and the visual system CTF graphed together. The area between the two curves has been designated the modulation transfer function area, or MTFA (Borough, et al, 1967 and Snyder, 1974). The MTFA provides a value that could be considered to be the information bandpass of the display/observer system. Any contrast value outside of this area either cannot be produced by the display system (above the MTF) or cannot be detected by the observer (below the CTF). Furthermore, the intersection of these two curves indicates the highest spatial frequency the display can produce that the observer can detect; also known as the limiting resolution of the system.

It has been proposed that the MTFA might be a reasonable indicator of image quality since it does combine characteristics of both human vision and display capability. Many variations of this fundamental concept have been proposed and tested (Task, 1979). Table 6 provides a short list of some of the variations that have been proposed.

The objective of each of these measures of image quality is to manipulate the contrast and spatial frequency axes of the MTF and CTF such that the resulting area linearly relates to human visual performance.

Table 6. Image quality metrics.

METRIC	DESCRIPTION
Modulation Transfer Function Area (MTFA)	Area between the display system MTF and the observer contrast threshold function.
Log MTFA	Logarithm of the MTFA
Limiting Resolution	Intersection of display MTF with observer CTF
Log Bandlimited MTFA	Logarithm of the area between the display MTF and the observer contrast discrimination threshold above two cycles/degree.*
Integrated Contrast Sensitivity (ICS) (van Meeteren, 1973)	The integral of the ratio of the display MTF and observer CTF

* Note: The contrast discrimination threshold function describes the amount of contrast an observer requires using a square-wave test pattern to just determine that it is a square-wave pattern and not a sine-wave pattern (Campbell and Robson, 1968).

TARGET RECOGNITION AND DETECTION STUDY I

To test the predictive power of several image quality metrics, a video based target recognition and detection study was conducted (Task, 1979). The objective of the study was to investigate the correlation between the various image quality metrics and observer performance for both a target recognition task and a target detection task.

<u>Summary</u> <u>of</u> <u>Study</u>: A total of 72 subjects participated; all were checked for 20/20 Snellen acuity. Ages for the 36 male and 36 female subjects ranged from 18 to 30 years. Subjects were seated in front of a video monitor at a distance of 28 inches. For the target recognition task, a target would appear in the center of the screen too small to be recognized and then would slowly increase in size until the subject could determine which of 6 targets was present. The targets were randomly presented in each of 4 orientations for a total of 24 presentations per subject. For the target detection task, an aerial terrain view was presented simulating the view from a low flying aircraft. The subject was prebriefed on the targets. Targets consisted of a set of large petroleum storage tanks. Two simulated altitudes were used: 1000 feet and 2000 feet.

A total of nine display system MTF conditions were included in the study. These included all combinations of three bandwidths (6, 1, 0.4 MHz) and three maximum contrast ratio settings (50:1, 50:5, 50:15). Eight subjects participated in each of the nine MTF conditions.

For the target recognition task, the angular subtense of the target at recognition was used as the dependent performance variable. Slant range (in simulated feet) to target at detection was the dependent variable selected for the target detection task.

Results: For the target recognition task, the average angular subtense of the target at recognition was calculated for each subject. This provided eight performance measures (one from each subject) for each of the nine display system conditions. The overall average performance for each display condition was the average performance of the eight subjects. This resulted in nine performance measures (one for each display condition) that could be correlated with calculated image quality metrics to determine which metrics best related to performance. Table 7 is a summary of these correlations.

The target detection task was divided into two parts by simulated altitude. The average slant range to target at detection for each condition was calculated as the performance measure and correlated with the image quality metrics as in the target recognition study. Table 7 also shows these results.

As should be evident from Table 7, all of the image quality metrics investigated correlated to some degree with human observer performance for both the target recognition task and the target detection task. The logarithm of the bandlimited MTFA (BLMTFA) correlates best overall. This would imply that the midrange spatial frequencies (2 - 8 cpd) are most important for the type of tasks investigated since the log BLMTFA emphasized this portion of the area more so than the other metrics.

Table 7. Correlations between image quality metrics and performance - Study I.

METRIC	RECOGNITION	DETECTION (1000ft)	DETECTION (2000ft)
MTFA	-0.81	0.83	0.72
Log MTFA	-0.88	0.87	0.78
Limiting Res	-0.76	0.78	0.70
Log BLMTFA	-0.95	0.93	0.88
ICS	-0.82	0.84	0.72

Note: A total of 19 image quality metrics were tested in this study; see Task, 1979 for more information.

This study used a general contrast threshold function (Campbell and Robson, 1968) to calculate all of the image quality metrics for the nine display conditions instead of measuring the CTF for each subject. This was done as a matter of convenience. Thus, the changes in the value of the image quality metrics were due solely to the display system MTF. Almost all of the image quality metrics demonstrated a reasonable correlation with performance (although some were obviously better than others), implying that the use of a general CTF was reasonable. Since the CTF may vary significantly from individual to individual, there have been some claims that these differences are significant (Ginsburg, 1986). The next question is whether or not using each individual's CTF in the calculation of image quality metrics will result in metrics that relate to performance. The following study was designed to investigate this area as a secondary objective.

TARGET RECOGNITION STUDY II

This study was primarily designed to investigate the effects of monochrome displays of different colors on target recognition performance (Pinkus, 1982) with prediction of individual performance differences from vision measurements as a secondary objective. The same imagery and procedure were used as in the previously described target recognition task.

Summary of Study: A total of 12 college aged subjects participated in this study. A total of six display conditions were established: all combinations of three colors (red, green, white) and two contrast ratios (40:1 and 2:1). A total of 5 vehicle targets served as the stimulus set and were presented to each subject in each of four orientations. All subjects participated in all conditions. The Snellen acuity of each subject was measured by an optometrist and the contrast threshold function of each subject for each color was measured by a separate vision research group. The acuity data, CTF data and visual performance data were not exchanged between the various research groups until after the data collection was complete. This eliminated any possibility of experimenter effect since each of these sets of data were obtained independently.

All subjects were required to have 20/20 or better vision, corrected or uncorrected (some subjects wore glasses). The presentation order of the stimulus material was randmomized to prevent learning the order of presentation. The video image was set to 7.5 inches high by 10 inches wide at a distance of 28 inches. A standard 525 line rate, 30 hertz frame rate, 2:1 interlace white P-4 phosphor CRT display was used for all presentations. The red and green conditions were simulated using color filters (a neutral density filter was used for the white condition to keep all the luminance conditions equal).

Results: Fortunately, the subjects varied considerably in their CTFs (thresholds differed by as much as a factor of 10 between individuals for some spatial frequencies)

so there was a very good range of CTFs to test the effect on visual performance. The average angular subtense of the target at recognition was calculated for each subject for each of the six display conditions. Since color was found to have no impact on performance, the data were divided into two groups: high contrast and low contrast. For each contrast condition, image quality metrics were calculated for each subject and color. Since the MTF of the display remained constant for each contrast condition, the only factor to change the value of the image quality metric was the CTF of the subject. The image quality metrics for each subject and color combination were then correlated with performance for the high contrast condition, the low contrast condition and then both conditions combined. Table 8 is a summary of these results.

From the correlations in Table 8, it is apparent that the effect of the individual CTF on the image quality metrics did not result in a measure that correlated with performance. The implication is that the difference in CTFs between normal individuals does not have an impact on visual performance for the types of tasks investigated.

Table 8. Correlation between image quality metrics and performance - Study II.

METRIC	LOW CONTRAST	HIGH CONTRAST	BOTH CONDITIONS
MTFA	-0.27	0.01	-0.58
Log MTFA	-0.27	0.00	-0.58
Limiting Res	-0.24	0.01	-0.52
Log BLMTFA	*	*	*
ICS	-0.01	0.26	-0.20

* Note: These values could not be calculated since the discrimination threshold curves for these subjects were not measured.

From the results of the studies presented, there is one apparent and significant conclusion concerning the role of the contrast threshold function (or contrast sensitivity function) in image quality metrics. Namely, a general contrast threshold function may be used to calculate image quality metrics. The effect of individual's CTFs (or CSFs) does not contribute to the prediction of visual performance for subjects with normal vision even though the differences in these CSFs may be as high as a factor of 10 between individuals at various spatial frequencies.

It is difficult to determine which image quality metric is the best since performance may vary considerably depending on the specific task required of the observer. From the studies described, the log bandlimited modulation transfer function area correlated best overall, however, other measures such as the MTFA and log MTFA were not far behind.

This paper has reviewed the basic physical, electrical, and optical characteristics of CRT, HUD, and HMD systems. The measurement techniques such as the MTF, convergence, and collimation were described in detail. The last part presented the results of two studies that investigated various methods to combine CRT display measurements with the human visual system's resolution and detection capabilities.

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